(12)

AD-A172 114

David W. Taylor Naval Ship Research and Development Center
Bethesda, MD 20084-5000

DTNSRDC/SPD 1199-01 September 1986
Ship Performance Department

Research and Development Report

Vertical Plane and Roll Motion Stabilization of SWATH Ships

by

Ernest E. Zarnick

DTNSRDC/SPD 1199-01 Vertical Plane and Roll Motion Stabilization of SWATH Ships

86 9 19 05

MAJOR DTNSRDC TECHNICAL COMPONENTS

- COMMANDER 00
  - TECHNICAL DIRECTOR 01
    - OFFICER IN CHARGE CARDEROCK 05
    - SHIP SYSTEMS INTEGRATION DEPARTMENT 12
    - SHIP PERFORMANCE DEPARTMENT 15
    - AVIATION AND SURFACE EFFECTS DEPARTMENT 16
    - STRUCTURES DEPARTMENT 17
    - COMPUTATION, MATHEMATICS & LOGISTICS DEPARTMENT 18
    - SHIP ACOUSTICS DEPARTMENT 19
    - CENTRAL INSTRUMENTATION DEPARTMENT 29
    - 04 OFFICER IN CHARGE ANNAPOLIS
    - 27 PROPULSION AND AUXILIARY SYSTEMS DEPARTMENT
    - 28 SHIP MATERIALS ENGINEERING DEPARTMENT

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

A172 114

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION Unclassified	1b RESTRICTIVE MARKINGS None
2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release: Distribution unlimited
2b DECLASSIFICATION/DOWNGRADING SCHEDULE	
4 PERFORMING ORGANIZATION REPORT NUMBER(S) DTNSRDC/SPD 1199-01	5 MONITORING ORGANIZATION REPORT NUMBER(S)
6a NAME OF PERFORMING ORGANIZATION David W. Taylor Naval Ship R&D Center 6b OFFICE SYMBOL (If applicable)	7a NAME OF MONITORING ORGANIZATION
6c ADDRESS (City, State, and ZIP Code) Ship Performance Department Bethesda, Maryland 20084	7b ADDRESS (City, State, and ZIP Code)
8a NAME OF FUNDING/SPONSORING ORGANIZATION 8b OFFICE SYMBOL (If applicable)	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c ADDRESS (City, State, and ZIP Code)	10 SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO 62543N PROJECT NO TASK NO RS43421S WORK UNIT ACCESSION NO DN178067

11 TITLE (Include Security Classification)

Vertical Plane and Roll Motion Stabilization of SWATH Ships

12 PERSONAL AUTHOR(S)

13a TYPE OF REPORT	13b TIME COVERED FROM ____ TO ____	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT

16 SUPPLEMENTARY NOTATION

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

A method has been developed to rapidly assess the effects of active fins on the vertical motions (platforming and contouring modes) and/or the roll motion of a SWATH ship in waves. The method combines Linear Quadratic Theory (LQT) of optimal control for obtaining the fin control law with the SWATH Seakeeping Evaluation Program (SSEP). The nonlinearities produced by the fin angle and fin rate saturation are approximated by placing limiting values on their corresponding values in a seaway. This permits frequency domain computations of the stabilized motions which is more consistent with LQT and more cost effective than those computed in the time domain. A description of the procedure and sample results are provided.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21 ABSTRACT SECURITY CLASSIFICATION
22a NAME OF RESPONSIBLE INDIVIDUAL	22b TELEPHONE (Include Area Code) / 22c OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

CONTENTS

FIGURES

FIGURES (CONTINUED)

TABLES

NOTATION

A_{ik}	Added mass coefficient in the ith mode due to motion in the kth mode
$\mathbf{A}$	System matrix
B_{ik}	Damping coefficient in the ith mode due to motion in the kth mode
$\mathbf{B}$	Control matrix
b_{nm}	Elements of control matrix
C_{ik}	Restoring coefficient in the ith mode due to motion in the kth mode
d_A	Aft fin angle
d_F	Forward fin angle
F_i	Wave exiting force or moment in the ith mode
$\mathbf{F}$	Vector notation for F_i
$\mathbf{G}$	Gain matrix
G_{rn}	Elements of gain matrix
I_i	Mass moment of inertia about the ith mode for i = 4, 5, 6
L_b	Distance from CG to bow
M	Mass of ship
P	Wave height/ship length (for normalizing angular motions)
$\mathbf{Q}$	Weigthing matrix of state variables in cost functional
$\mathbf{R}$	Weighting matrix of control variables in cost functional
$\mathbf{u}$	Control variables
z	Heave motion
z_b	Vertical motion at bow
β	Fin angle
ϕ	Roll angle
η	Wave surface elevation
θ	Pitch angle
ψ	Yaw angle

ABSTRACT

A method has been developed to rapidly assess the effects of active fins on the vertical motions (platforming and contouring modes) and/or the roll motion of a SWATH ship in waves. The method combines Linear Quadratic Theory (LQT) of optimal control for obtaining the fin control law with the SWATH Seakeeping Evaluation Program (SSEP). The non-linearities produced by the fin angle and fin rate saturation are approximated by placing limiting values on their corresponding values in a seaway. This permits frequency domain computations of the stabilized motions which is more consistent with LQT and more cost effective than those computed in the time domain. A description of the procedure and sample results are provided.

ADMINISTRATIVE INFORMATION

This investigation was sponsored by the Chief of Naval Research, Office of Naval Technology OCNR-211 under the Ship and Submarine Technology Program, Program Element 62543N thrust area RS43421J (SUSNLO), Surface Ship Nothern Latitudes Operations.The DTNSRDC work unit number is 1-1506-620-25.

INTRODUCTION

One of the attributes of a well designed SWATH ship is its superior performance in waves. These ships are normally equipped with fins to improve their vertical stability at high speeds and to further improve their motion characteristics by the introduction of additional damping in the vertical plane. More recently the fins have been exploited as a means of turning the vehicle in lieu of vertical rudders. By suitable activation of the fins further reductions in the vertical plane motions and/or the roll motions are possible. The resulting increase in ship operability in a seaway enhances the mission capabilities of the SWATH ship.

A method has been developed to rapidly assess the effects of active fin stabilization on the vertical motions (platforming or contouring mode) and/or

roll motion of SWATH ships in waves. The method employs the Linear Quadratic Theory (LQT) of optimal control to define the gains in a control law for activating the fins. The resulting control law is a linear function of the state variables which can be readily incorporated into the SWATH Seakeeping Evaluation Program (SSEP) for rapid assessment of the effects of activated fins on the ship performance in waves.

The LQT was first applied to the SWATH ship by Ware[1,2] for the vertical motions in both the platforming and contouring modes. The essential difference between Ware's approach and the present method is that here the computations of the stabilized motion are made in the frequency domain; whereas, previously they were computed in the time domain. The computations are not only necessary to determine the stabilized motion, but to assure that the limiting fin angles and fin rates are not exceeded. The gains determined by LQT assume the availability of an infinite amount of fin angle and fin rate.

Computations in the time domain more accurately simulate the nonlinearities due to fin angle and fin rate saturation, but such calculations are very costly in computer time. A more cost effective alternative is to retain a linear representation of the ship system (so that computations can be made in the frequency domain) and to account for the limitations of fin angle and fin rate by constraining their corresponding rms values in proportion to their limiting values. This accords greater consistency in the method since a linear model is retained throughout the computations.

In addition to the above the LQT has now been applied to the reduction of the SWATH roll motion. The same general approach that was used in the case of the vertical plane motions has been extended to the transverse plane including roll,sway and yaw motions, but with stabilization in the roll mode only. The SSEP program was also modified so that a combination of both vertical plane and roll stabilization can be applied simultaneously. The optimization of the control system for the vertical plane motions and roll motion are computed separately and combined in a fixed proportion.

APPLICATION OF LINEAR QUADRATIC THEORY

BASIC PROCEDURE

The design of an optimum linear control with quadratic criteria for a SWATH ship assumes that the ship dynamics can be represented by a linear system of first order differential equations with constant coefficients in the form of

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) \qquad [1]$$

where $\mathbf{x}$ is the n-dimensional state vector,

$\mathbf{u}$ is the m-dimensional input(control) vector,

$\mathbf{A}$ is an n x n matrix,

and $\mathbf{B}$ is an n x m matrix.

The performance criteria for determining the optimal control input $\mathbf{u}(t)$ is the minimization of the cost functional

$$J(\mathbf{u}) = {}^1/_2 \int \mathbf{x}^T \mathbf{Q}\, \mathbf{x} + \mathbf{u}^T \mathbf{R}\, \mathbf{u}\, dt, \qquad [2]$$

where $\mathbf{x}^T$ is the transpose of $\mathbf{x}$

$\mathbf{u}^T$ is the transpose of $\mathbf{u}$

$\mathbf{Q}$ is an n x n positive semidefinite matrix

and $\mathbf{R}$ is a r x r positive definite matrix.

What we wish to do, by suitable selection of the elements of $\mathbf{Q}$ and $\mathbf{R}$, is to drive the state $\mathbf{x}(t)$ to zero without excessive expenditure of control energy. In the case of the SWATH, we would like to make the ship motions small without the use of unnecessarily large controls. Large fin angles are limited by the inception of cavitation, stall angle, structural loading, and in the case of fin rate, the machinery size, weight, and cost.

The solution to this problem, obtained by the use of the minimum principle, can be found in many text books[3] on optimal control and results in a control law which is a function of the state variables,i.e.,

$$\mathbf{u}(t) = -\mathbf{G}\mathbf{x}(t) \tag{3}$$

where $\mathbf{G} = \mathbf{R}^{-1}\mathbf{B}^T\mathbf{K}$. [4]

The matrix $\mathbf{K}$ is obtained by solving the matrix Riccati equation

$$0 = \mathbf{A}^T\mathbf{K} + \mathbf{K}\mathbf{A} + \mathbf{Q} - \mathbf{K}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{K} \ . \tag{5}$$

The matrix Ricatti equation is nonlinear, and normally can not be solved in closed-form; however, it is amenable to solution on a digital computer. A computer program is in use at the Center which can solve this equation given the matrix definition of the system and the matrices defining the weighting factors in the cost functional.

Existence of a solution requires that the system, as defined in equation [1], be both controllable and observable. In simple terms, controllable means that it is possible to drive the state of the system to zero and observable means that the state(which must be known to construct the optimal control law) can be determined from the output of the system. It should be noted that these terms have precise mathematical definitions which can be found in many textbooks on optimal control. Another requirement is that the eigenvalues of the closed loop system matrix $(\mathbf{A} - \mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{K})$, obtained by substituting equations [3] and [4] into equation [1], must have negative real parts for an optimal solution to exist, which logically means that the optimal system must be stable. The controlled system itself does not need to be stable, but the optimal or closed loop system must be strictly stable.

In the following applications it is necessary to make adjustments in the the equations of motion for the SWATH ship in order to conform to the requirements of the Linear Quadratic Theory of optimal control. Added mass and damping coefficients, which are frequency dependent in the ship motion problem, are assumed to be constant in order to conform to the format in equation [1]. In the optimization process the coefficient values at a single frequency are used to represent the ship system throughout the entire frequency range. The frequency selected is usually that at which maximum motions occur; although, several sets of coefficients can be used and an average taken of the results.

VERTICAL PLANE MOTIONS

The equations of motion in the vertical plane are usually presented in the more familiar form,

$$\begin{aligned} (M + A_{33})\ddot{Z} + B_{33}\dot{Z} + C_{33}Z + A_{35}\ddot{\theta} + B_{35}\dot{\theta} + C_{35}\theta &= F_3 \\ A_{53}\ddot{Z} + B_{53}\dot{Z} + C_{53}Z + (I_5 + A_{33})\ddot{\theta} + B_{55}\dot{\theta} + C_{55}\theta &= F_5 \end{aligned} \qquad [6]$$

In the case of the SWATH ship, there is a coupling of the surge motion into the pitch motion. This coupling can be considered to be absorbed into the right hand side of equation [6] because there is no corresponding coupling of pitch back into surge.

Rearranging equation [6] into matrix format and adding terms representing the controller we have:

$$\begin{bmatrix} (M+A_{33}) & 0 & A_{35} & 0 \\ 0 & 1 & 0 & 0 \\ A_{53} & 0 & (I_5+A_{55}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \ddot{Z} \\ \dot{Z} \\ \ddot{\theta} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -B_{33} & -C_{33} & -B_{35} & -C35 \\ 1 & 0 & 0 & 0 \\ -B_{53} & -C_{53} & -B_{55} & -C_{55} \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{Z} \\ Z \\ \dot{\theta} \\ \theta \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} \\ 0 & 0 \\ b_{31} & b_{32} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} d_F \\ d_A \end{bmatrix} + F \qquad [7]$$

where d_F is the forward fin angle

d_A is the aft fin angle

and b_{11} through b_{32} are constants to convert fin angle to heave force and pitch moment.

In matrix notation equation [7] can be written as,

$$\mathbf{T}\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{d} + \mathbf{F} \qquad [8]$$

which, by simple matrix algebra reduces to

$$\dot{\mathbf{x}} = \mathbf{T}^{-1}\mathbf{A}\mathbf{x} + \mathbf{T}^{-1}\mathbf{B}\mathbf{d} + \mathbf{T}^{-1}\mathbf{F}$$

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{d} + \mathbf{F} \qquad [9]$$

When the disturbance **F** is Gaussian white noise, the optimal solution to equation [9] is identical to that for equation [1]. A hueristic justification can be made that since the system can not anticipate a white noise disturbance (because it is completely random), the optimum solution must be that which drives the undisturbed state to zero (homogeneous solution). For shaped noise, as in the case of the heave and pitch exciting force and moment, the optimal solution is dependent upon additional state variables which determine the spectra shape.

As Ware[2] has shown, these variables (which shape the spectra) do not affect the optimal gain factors associated with the system state variables, and since they are not observable they are neglected. A more detailed discussion of this point is presented by Ware[2].

The above formulation of the equations of motion are most useful for operation in the platforming mode, i.e., level flight. In this case both the pitch and heave motion need to be minimized. A desirable alternative is operation in the contouring mode, i.e., ship movement parallel to the wave surface. Optimization of the fin control system for this type of operation can be obtained by reformulating the equations of motion appropriately with the

introduction of relative bow motion as a state variable. The relative bow motion can then be minimized to achieve contouring operation.

The absolute bow motion at a distance L_b from the CG is given by,

$$Z_b = Z + \theta L_b \tag{10}$$

and the corresponding relative bow motion is,

$$Z_{rb} = Z_b - \eta_b \tag{11}$$

where η_b is the surface elevation at L_b.

The new state variables are:

$$\mathbf{x}_b = \begin{bmatrix} Z_b-\eta_b \\ Z_b-\eta_b \\ \theta \\ \theta \end{bmatrix} = \begin{bmatrix} 1 & 0 & -L_b & 0 \\ 0 & 1 & 0 & -L_b \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} Z \\ Z \\ \theta \\ \theta \end{bmatrix} - \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} \eta_b \\ \eta_b \end{bmatrix} \tag{12}$$

or

$$\mathbf{x}_b = \mathbf{Cx} + \mathbf{Dw} \tag{13}$$

from which,

$$\mathbf{x} = \mathbf{C}^{-1}\mathbf{x}_b - \mathbf{C}^{-1}\mathbf{Dw}. \tag{14}$$

Substituting eq.[14] into eq.[9], and after redefinition of some of the variables we get,

$$\mathbf{x}_b = \mathbf{A}_b\mathbf{x}_b + \mathbf{B}_b\mathbf{u} + \mathbf{F}_b\mathbf{v}_b \tag{15}$$

which is in the form of equation[9] and amenable to LQT techniques.

The design of an optimal fin control system for pitch stabilization is usually accomplished in three steps. First, the coefficients defining the ship system for a particular heading angle and ship speed are obtained throughout the frequency range using the SWATH Ship Evaluation Program (SSEP) modified slightly to output these data in suitable form on file. Second, the optimal gains are obtained by solving the Ricatti equation using the SWATH Ship Optimization Program (SWOPT) for constant coefficients selected at a particular frequency (or for several frequencies). Finally, a ship operability assessment is made using a version of SSEP with active fin control dynamics incorporated to verify the results over the entire range of selected speeds and headings.

ROLL MOTION

The design of an optimum controller for the roll motion of a SWATH ship is essentially the same as that for pitch except that the system involves three degrees of freedom ,i.e., sway, roll, and yaw. The equations of motion in the transverse plane are:

$$(M+A_{22})\ddot{Y} + B_{22}\dot{Y} + (A_{24}-Mz_o)\ddot{\phi} + B_{24}\dot{\phi} + A_{26}\ddot{\psi} + B_{26}\dot{\psi} + C_{26}\psi = F_2$$

$$A_{42}\ddot{Y} + B_{42}\dot{Y} + (I_4+A_{44})\ddot{\phi} + B_{44}\dot{\phi} + C_{44}\phi + (A_{46}-I_{46})\ddot{\psi} + B_{46}\dot{\psi} + C_{46}\psi = F_4 \qquad [16]$$

$$A_{62}\ddot{Y} + B_{62}\dot{Y} + (A_{64}-I_{64})\ddot{\phi} + B_{64}\dot{\phi} + (I_6+A_{66})\ddot{\psi} + B_{66}\dot{\psi} + C_{66}\psi = F_6.$$

Coefficients associated with the yaw angle are due to body lift contributions and fin lift (when the fins are canted). Also, there is no restoring force in sway. The net result is that the system is neutrally stable in sway and may possibly be unstable in yaw.

As in the case of the vertical plane motions, we can rearrange eq. [15] and add the controller terms to get,

$$\begin{bmatrix} (M+A_{22}) & 0 & (A_{24}-Mz_o) & 0 & A_{26} & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ A_{42} & 0 & (I_4+A_{44}) & 0 & (A_{46}-I_{46}) & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ A_{62} & 0 & (A_{64}-I_{64}) & 0 & (I_6+A_{66}) & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \ddot{Y} \\ \dot{Y} \\ \ddot{\phi} \\ \dot{\phi} \\ \ddot{\psi} \\ \dot{\psi} \end{bmatrix} =$$

$$\begin{bmatrix} -B_{22} & 0 & -B_{24} & 0 & -B_{26} & -C_{26} \\ 1 & 0 & 0 & 0 & 0 & 0 \\ -B_{42} & 0 & -B_{44} & -C_{44} & 0 & -C_{46} \\ 0 & 0 & 1 & 0 & 0 & 0 \\ -B_{62} & 0 & -B_{64} & 0 & 0 & -C66 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{Y} \\ Y \\ \dot{\phi} \\ \phi \\ \dot{\psi} \\ \psi \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} \\ 0 & 0 \\ b_{31} & b_{32} \\ 0 & 0 \\ b_{51} & b_{52} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} d_F \\ d_A \end{bmatrix} \qquad [17]$$

Again, as in the case of the vertical motions, eq.[17] can be written in simplified matrix notation as,

$$\mathbf{M}\dot{\mathbf{x}}_r = \mathbf{C}\mathbf{x}_r + \mathbf{B}_r\mathbf{d} + \mathbf{F}_r \qquad [18]$$

or,

$$\dot{\mathbf{x}}_r = \mathbf{A}_r\mathbf{x}_r + \mathbf{B}_r\mathbf{d}_r + \mathbf{F} \qquad [19]$$

Equation [19] is in the same form as equation [9] or (upon neglecting the disturbance matrix) eq.[1], and is amenable to LQT optimal control methods. However, in its present form, eq.[19] presents some practical difficulties. As previously indicated, Linear Quadratic Theory requires that the system be controllable and the closed loop system be stable. This implies that (in

addition to the roll motion) the sway and yaw motions must be stabilized which would extract an unnecessary and expensive control system penalty at wave encounter frequencies. In order to circumvent this dilemma an artificial restoring force has been introduced in the sway motion and, when necessary, the yaw motion simulating the action of a rudder or canted fins. This provides stability to the system and eliminates the need to stabilize the sway and yaw motions simply to accommodate the mathematical requirements of the theory. The dynamics of the system may be altered slightly by this approach, but this does not seem to have a significant influence upon the resulting optimum controller for roll motion reduction.

The procedure followed in the design of an optimal controller for the roll motion is identical to that for pitch. A modified version of the SWATH Ship Evaluation Program (SSEP) is employed to determine the coefficients in the equations of motion of the ship system in the tranverse plane for specific heading angles and speeds. The optimal gains are then obtained by solving the Ricatti equation using a modified version of the SWATH Ship Optimization Program (SWOPT). A ship operability assessment is then made using a version of SSEP with active fin control dynamics incorporated to verify the results over the range of heading angles and speeds selected for roll stabilization.

SAMPLE DESIGN OF OPTIMUM CONTROLLER FOR PITCH STABILIZATION

The recent Naval Studies Board (NSB) SWATH Ship study provides a illustrative example of the design of a controller for pitch stabilization using the presently described method. In the normal course of this study the SWATH Ship Evaluation Program (SSEP) was used to:(1) design a pair of inactive fins which would ensure vertical plane stability throughout the operating speed range, and (2) provide a seakeeping assessment of the ship hull in various ocean environments. The criteria for the seakeeping assessment include limits on the ship motions, accelerations at various locations, wetness, and slamming. A detailed description of this procedure has been published by McCreight and Stahl[4]. Table 1 presents a list of characteristics for the NSB SWATH design and Table 2 presents dimensions of the resulting fin design.

Table 1. Naval Studies Board SWATH Characteristics

Units	English	Metric
Length (ft), (m)	382.00	116.00
Displacement (ton), (tonne)	7023.00	6912.00
LCB (ft), (m)	179.06	54.58
LCF (ft), (m)	172.00	52.43
KB (ft), (m)	12.41	3.78

Table 2. Naval Studies Board SWATH Fin Geometry

	Forward Fin		Aft Fin	
Units	English	Metric	English	Metric
Chord (ft), (m)	5.90	1.80	14.46	4.41
Span (ft), (m)	11.81	3.60	28.92	8.81
Maximum Thickness (ft), (m)	0.89	0.27	2.17	0.66
Distance from Quarter Chord to CG (ft), (m)	145.85	44.40	-132.50	-40.39
Aspect Ratio	2.00		2.00	
Aft/Fwd Fin Area Ratio		6.00		

The seakeeping assessment of the ship equipped with the above inactive fins was found to be excellent in head waves, but in following waves the criteria limiting the significant pitch amplitude to three degrees was exceeded in progressively lower sea states as the speed increased. The relatively small GM_L of this SWATH ship results in a long natural pitch period; consequently, in head waves the ship operates in the super critical range. The frequencies of encounter with the waves are much greater than the natural pitch period where the pitch motion response is low. In following waves the frequencies of encounter with the waves concentrates more wave energy near the natural pitch period and this results in higher pitch motion response.

The strategy for improving ship performance in this instance is rather straight forward: reduce the pitch motion of the ship in following waves without adversely affecting the other criteria while keeping within the physical limitations of the controller. The physical limitations imposed upon the

controller are the maximum permissible fin angle or fin stop and the maximum fin rate. In order to accommodate these nonlinear factors in the linear frequency domain calculations and avoid so called "bang-bang" operation, the standard deviation of the fin angle and fin rate are restricted as follows:

$$2.146\ \beta \leq \beta_{stop}$$
$$3.035\ \beta \leq \beta_{max}. \qquad [20]$$

where β_{stop} = fin stop angle

and β_{max} = maximum fin rate

These criteria have been adopted from Cox and Adrian[5] who applied them to monohull antiroll fin designs. The criteria imply that not more than one fin excursion in ten will exceed the fin angle limit and that the maximum fin rate will not be exceeded more than once in one hundred excursions. Cox and Adrian also provide a means for determining upper bounds on the fin stop angle which is dependent upon factors such as fin stall, cavitation inception, and structural strength. The maximum fin rate is a factor governed by machinery size, weight, and cost.

Since the sizes of the inactive fins were determined by the requirement of stability at high forward speeds it was considered expedient to maintain the same size for the active fins. A smaller set of active fins may have provided the necessary stability, but in the event of failure of fin activation this stability would be lost and the ship would not have been able to maintain its top operating speed. Optimal gains were computed for the existing set of fins.

The controller gains were optimized for following sea conditions at a speed of twenty knots. The procedure requires the selection of a set of weighting factors in the cost functional, eq.[2], to achieve the maximum pitch reduction with the imposed constraints on the fin deflection and rates. Initially, a maximum fin angle of 20 degrees and a fin rate of 10 degrees per

second were selected as limits, but it was found that they could be reduced slightly and still meet the desired objectives. The resulting optimum gain factors are shown in Table 3.

Table 3. Optimum Gain Factors for NSB Pitch Stabilization

Forward Fin				
Time Constant	G_{11}	G_{12}	G_{13}	G_{14}
1.4755	0.00	0.00	0.961	0.398
Aft Fin				
Time Constant	G_{21}	G_{22}	G_{23}	G_{24}
0.5537	0.00	0.00	-10.371	-3.676

A comparison of the pitch response with and without fin stabilization is presented in Figure 1. Figure 1 shows the variation of pitch with respect to wave frequency instead of frequency of encounter to avoid multivariable responses which occur in following waves.

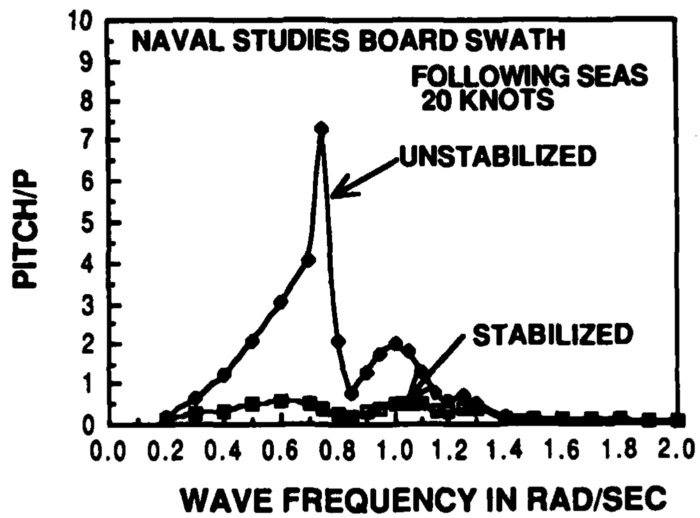

Figure 1. Pitch Response of NSB SWATH with and without Fin Stabilization

The gains obtained at 20 knots were also used at 15 and 25 knots and at other heading angles with good results. A slight improvement could be obtained in the overall performance by conducting separate optimization computations at 15 and 25 knots, but this was not considered essential. At a ship speed of 10 knots and lower in following waves and at all conditions in head waves the fins were not effective using the above gains. Fortunately, the performance of the ship is excellent without the use of active fins in head waves and acceptable at 10 knots or less in the following wave conditions. This can be seen in Figures 2 and 3 which compare the operability and the limiting wave heights for the ship with and without active fins at 15, 20, and 25 knots.

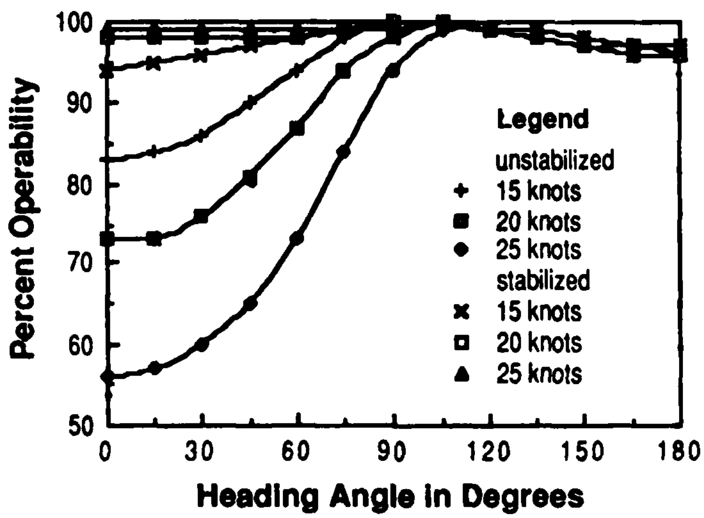

Figure 2. Percent Operability for NSB SWATH with and without Fin Stabilization

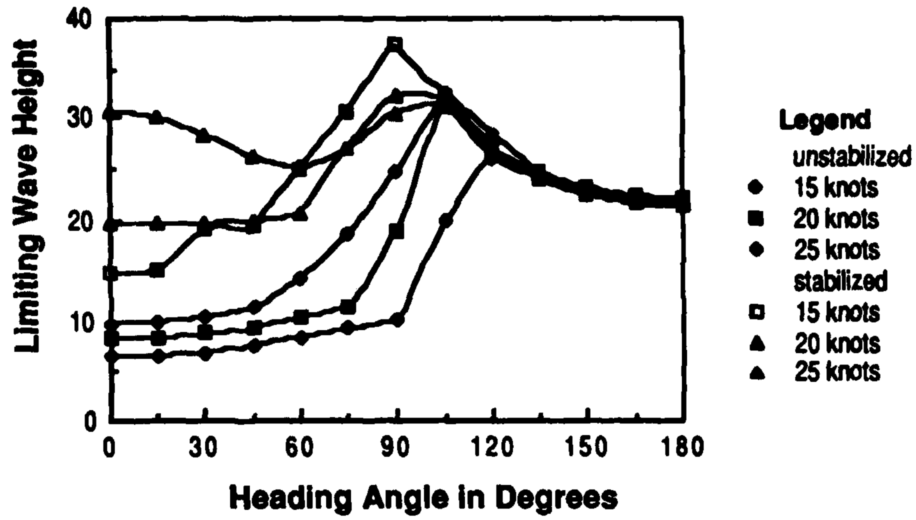

Figure 3. Limiting Wave Height for NSB SWATH with and without Fin Stabilization

It is evident from the results shown in Figures 1 through 3 that a significant improvement can be obtained in the seakeeping capabilities of the NSB SWATH ship by the implementation of active fin pitch stabilization.

SAMPLE DESIGN OF OPTIMUM CONTROLLER FOR COMBINED PITCH AND ROLL STABILIZATION

Some SWATH ships have shown a need for roll stabilization in addition to pitch stabilization in order to improve their seakeeping performance. A major part of this effort has been directed towards the application of LQT to this problem. The AGX SWATH is an example of a ship design in need of simultaneous roll and pitch stabilization.

As in the case of pitch motion stabilization, the size of the fins are dictated by the requirements of vertical plane stability at maximum forward speed (without the assist of activated fins). Optimal gains are computed separately for the roll stabilization and, if needed, the pitch stabilization of the ship. The deflection of the fins resulting from the combined efforts of

pitch and roll stabilization must still meet the requirements imposed by the maximum allowable fin stop angle and fin rate in accordance with eq.[20]. This further complicates the procedure for selecting the weighting factors in the cost functional.

The approach used in the AGX controller was to first stabilize the initial limiting factor(which was the pitch motion) and follow with the stabilization of the roll motion while ensuring that the fin deflections remained within their prescribed bounds. Table 4 presents the pertinent hull characteristics of the AGX SWATH

Table 4. AGX SWATH Characteristics

Units	English	Metric
Length (ft), (m)	332.8	101.4
Displacement (ton), (tonne)	4987.0	5067.0
LCB (ft), (m)	155.5	47.4
LCF (ft), (m)	156.0	47.5
KB (ft), (m)	10.4	3.2

The AGX SWATH was designed with a set of inactive fins to maintain stability in the vertical plane up to a speed of 20 knots. Following the procedure used in the case of the NSB SWATH, the same size fins were maintained for the AGX active fin controller design. The dimension of these fins are presented in Table 5.

Table 5. AGX SWATH Fin Geometry

	Forward Fin		Aft Fin	
Units	English	Metric	English	Metric
Chord (ft), (m)	12.86	3.92	15.75	4.80
Span (ft), (m)	15.43	4.70	18.90	5.76
Maximum Thickness (ft), (m)	1.93	0.59	2.36	0.72
Distance from Quarter Chord to CG (ft), (m)	134.25	40.92	-132.73	-40.46
Aspect Ratio	2.00		2.00	
Aft/Fwd Fin Area Ratio		6.00		

The optimum gain factors computed for the AGX SWATH ship are presented in Table 6 for pitch stabilization and in Table 7 for roll stabilization. Both the pitch and roll gains were optimized at a speed of 20 knots. The gain factors associated with the yaw and sway in Table 7 are zero since no weighting is given to the stabilization of these motions. They have been included only because they are inherent in the formulation of the mathematical problem.

Table 6. Optimal Gain Factors for AGX SWATH Pitch Stabilization

		Forward Fin		
Time Constant	G_{11}	G_{12}	G_{13}	G_{14}
1.5343	0.0	0.0	14.392	1.543
		Aft Fin		
Time Constants	G_{21}	G_{21}	G_{23}	G_{24}
1.1729	0.0	0.0	10.459	1.674

Table 7. Optimal Gain Factors for AGX SWATH Roll Stabilization

Forward Fin					
Gr_{11}	Gr_{12}	Gr_{13}	Gr_{14}	Gr_{15}	Gr_{16}
0.0	0.0	-28.758	-18.29	0.0	0.0
Aft Fin					
Gr_{21}	Gr_{22}	Gr_{23}	Gr_{24}	Gr_{25}	Gr_{26}
0.0	0.0	-36.10	-16.73	0.0	0.0

The above gains were used in an assessment of the operability and associated limiting wave heights on an annual basis for the AGX SWATH operating in the North Atlantic at 20 knots. Figure 4 presents the pitch response with and without stabilization at 20 knots for a heading angle of 60 degrees and Figure 5 present the corresponding roll response with and without stabilization for the same condition. The percent operability and limiting wave height variation with heading angle are presented in Figures 6 and 7 respectively.

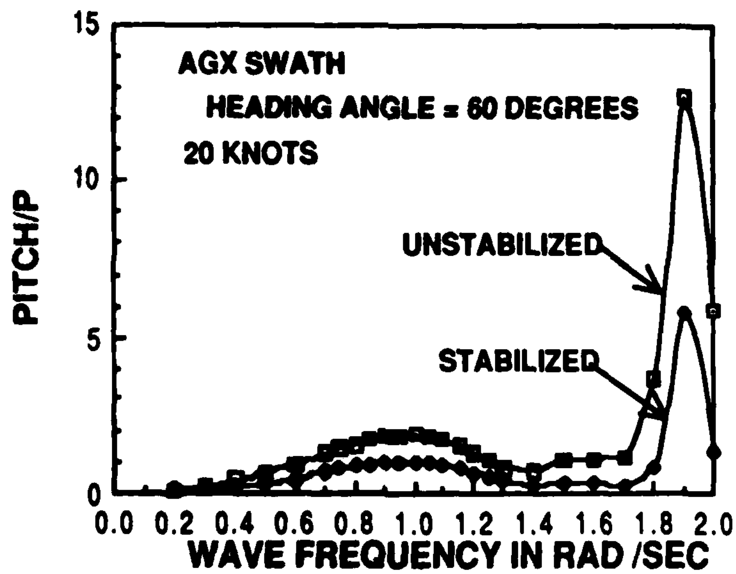

Figure 4. Pitch Response of AGX SWATH with and without Fin Stabilization

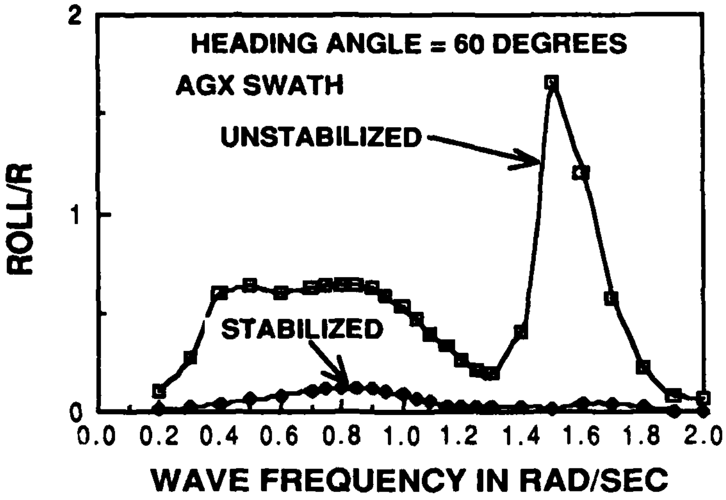

Figure 5. Roll Response of AGX SWATH with and without Fin Stabilization

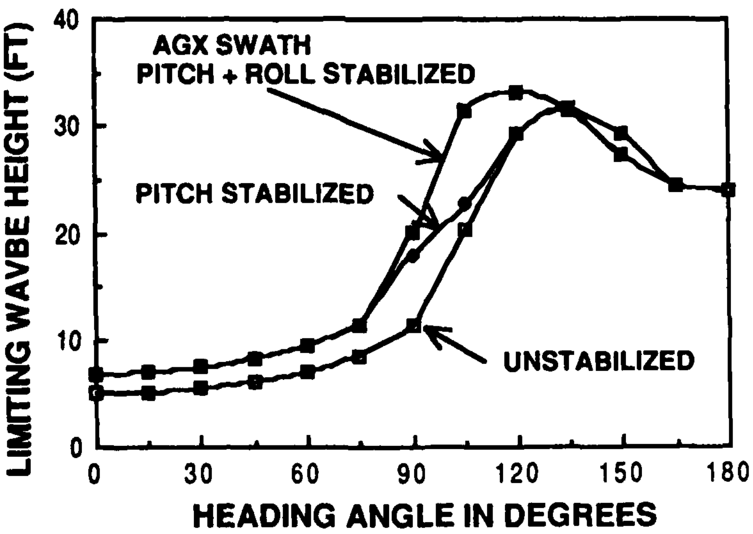

Figure 6. Limiting Wave Height for AGX SWATH with and without Fin Stabilization

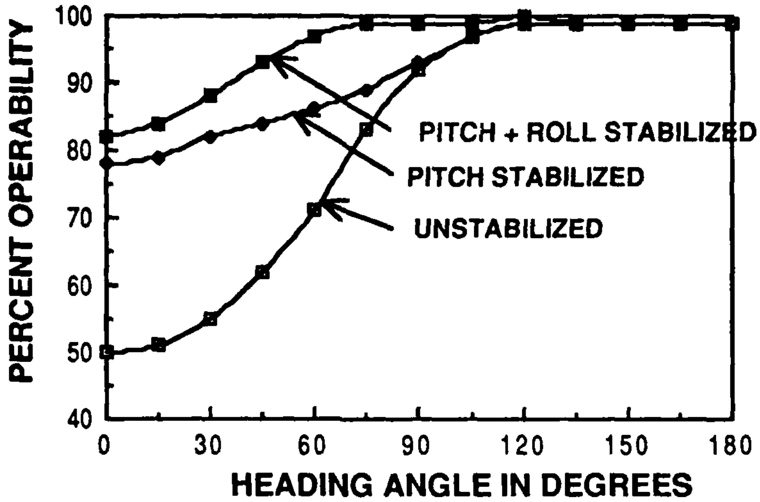

Figure 7. Percent Operability for AGX SWATH with and without Fin Stabilization

Figures 4 and 5 indicate that both large pitch and roll reductions can be realized by use of the activated fins. As shown in Figure 6, there is a large increase in the limiting wave height in following seas by the use of pitch stabilization which is still further increased in beam seas by the inclusion of roll stabilization. Figure 7 shows that there is a large increase in the percent operability from following seas through beam seas with combined pitch and roll stabilization.

SUMMARY AND CONCLUSION

In many instances the seakeeping performance of a SWATH ship can be greatly enhanced by the use of activated fins. A method has been developed which provides the naval architect with the necessary tools for designing active fin stabilizers for SWATH ships. Although, the basis of the method is highly complex the method is reasonably simple to execute and requires only a minimum knowledge or training in control theory.

The control law and associated gains are determined by the Linear Quadratic Theory of Optimal Control. This assumes that the ship can be mathematically represented by a linear system of equations with constant coefficients. Since the ship has frequency dependent coefficients, the optimal gains are determined at a single frequency. This frequency is selected to correspond to the frequency at which the motion to be stabilized is maximum or several frequencies can be selected and the gains averaged.

Optimal gains can be computed for stabilization in the vertical plane both in the contouring and platforming modes. The computer code for solving this problem in the vertical plane has been extended to compute the gains in the transverse plane for stabilizing the SWATH ship's roll motion.The vertical motion and roll motion can be combined to achieve stabilization in these modes simultaneously. The stabilized motions with fin activation are computed in the frequency domain with the SWATH Seakeeping Evaluation Program (SSEP); whereas, previously they were computed in the time domain to accommodate the nonlinear

behaviour introduced by fin angle and fin rate saturation. These nonlinearities are accounted for in the frequency domain by limiting their respective rms values to those which are statistical related to the fin stop angle and maximum fin rate. This approach has been successfuly used in the design of monohull antiroll fin stabilizers.

Sample results show that the seakeeping of SWATH ships, as measured in terms of limiting wave heights and operability in the ocean environment, can in some instances be greatly improved by the implementation of fin stabilization. The Naval Studies Board SWATH design, for example, showed a potential increase in operability from about twenty to thirty percent in following sea conditions at speeds ranging from 15 to 25 knots by stabilization of the pitch motion. In another example, the AGX SWATH design showed a 28 percent increase in operability in following seas at a speed of 20 knots with pitch motion stabilization. An additional 10 percent improvement in operability was achieved

primarily in beam seas by the addition of roll stabilization.

In summary, computer codes are now available that enables the ship designer to rapidly assess the effects of active fins stabilization on the vertical and/or roll motion on the seakeeping performance of SWATH ships in a variety of ocean environmental conditions.

REFERENCES

1. Ware, John R., Best, John F. and Scott, Valerie A., "Application of Optimal Control Techniques to SWATH Vertical Plane Control", ORI Technical Report 1682, March 1980

2. Ware, John R., and Scott, Valerie A., "Comparison of Platforming and Contouring Automatic Control Systems for SWATH Craft - An Optimal Approach," ORI Technical Report 1790, September 1980

3. Athans, Michael and Falb, Peter L., Optimal Control, An Introduction to the Theory and Applications, McGraw-Hill Book Company, 1966

4. McCreight, Kathryn K. and Stahl, Ralph, "Recent Advances in the Seakeeping Assessment of Ships," Naval Engineers Journal, May 1985

5. Cox, Geoffrey G. and Lloyd, Adrian R., "Hydrodynamic DEsign Basis for Navy Ship Motion Stabilization," SNAME Transactions, Vol. 85, 1977, pp. 51-93

DTNSRDC ISSUES THREE TYPES OF REPORTS:

1. **DTNSRDC reports, a formal series,** contain information of permanent technical value. They carry a consecutive numerical identification regardless of their classification or the originating department.

2. **Departmental reports, a semiformal series,** contain information of a preliminary, temporary, or proprietary nature or of limited interest or significance. They carry a departmental alphanumerical identification.

3. **Technical memoranda, an informal series,** contain technical documentation of limited use and interest. They are primarily working papers intended for internal use. They carry an identifying number which indicates their type and the numerical code of the originating department. Any distribution outside DTNSRDC must be approved by the head of the originating department on a case-by-case basis.